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High Level Impulse Sounds and Human Hearing: Standards, Physiology, Quantification

by Bruce E. Amrein and Tomasz R. Letowski

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14. ABSTRACT

Assessing the noise hazard of high level impulse sounds created by friendly and enemy weapons is of critical importance since hearing loss negatively impacts mission success and unit readiness, and creates a costly common Soldier disability. Noise hazard assessment tools must strike a balance between minimizing hearing injury and creating high lethality weapons that ensure battlefield superiority and survivability. Existing tools, e.g., the U.S. National Research Council's Committee on Hearing and Bio-acoustics's (CHABA) Damage Risk Criteria (DRC), are not applicable for a broad range of military blasts, such as from improvised explosive devices (IEDs). This report provides background information and justification for using the auditory hazard assessment algorithm for humans (AHAAH), which incorporates state-of-the-art knowledge about the human hearing system to predict and quantify hearing loss caused by high level impulse sounds. This 10-year-old extensively peer-reviewed model has immediate value as a health hazard assessment tool and a design tool for the military. It can predict the onset of hazard in the human ear much more accurately than other methods and simulate the behavior of various hearing protection devices (HPDs). Further, its foundations in physical phenomenology are generalizable to new weapon sounds. The model provides engineering insight into the loss process to promote safer, more effective designs.

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1. Background

The goal of powerful offensive weapons is to overwhelm the enemy by long range and highly accurate lethal strikes. In addition to creating the actual physical damage at distal locations, such weapons have a powerful psychological effect and prevent the enemy from moving close enough to cause reciprocal damage with their weapon systems. Unfortunately, the higher muzzle velocities, heavier projectiles, and higher pressure levels of more powerful weapon systems result in higher impulse noise levels and increased hearing loss risk for the operators. Therefore, both weapons developers and medical personnel must have appropriate criteria and operational models to certify weapon systems as safe for use. Consequently, in order to protect Soldiers from the harmful sounds of their own weapons, a realistic set of impulse noise auditory injury criteria needs to be developed. Such impulse noise criteria should specify noise exposure limits and the risk of hearing loss associated with them (see section 4.1) (Hodge and Price, 1978) and should have a form similar to the U.S. National Research Council's Committee on Hearing and Bio-acoustics' (CHABA) Damage Risk Criteria (DRC) for continuous and intermittent noises. Unfortunately all previous attempts to create such criteria or respective standards were too limited and failed to accurately specify auditory hazards across the significantly wide domain of impulsive sounds, leaving the current research community with a desperate search for a new solution. "At present there are no practical guidances how to access impulse noise risk criteria" (Starck et al., 2003, p. 71).

1.1 Industrial Occupational Noise Limits

Despite wide application in industrial settings, the hearing protection criteria specified in various existing industrial occupational safety standards, such as those issued by the U.S. Occupational Safety and Health Administration (OSHA), are not suitable for military applications. According to OSHA requirements, the permissible exposure level (PEL) cannot exceed 90 dB A-weighted[*] (85 dB A-weighted in some cases) as an 8-h, time-weighted average (TWA) level with maximum peak sound pressure level for impulsive noise less than 140 dBP C-weighted regardless of the shape of the impulse and its spectral content. The noise impulse is assumed to be a noise event that lasts less than a second. The 140 dBP[†] limit is independent of the duration of the noise impulse (up to 1 s) and there is no OSHA limit for the number of exposures to noise impulses. OSHA also adopted a 5-dB time-intensity exchange ratio meaning that for each 5 dB increase of noise level above 90 dB A-weighted the permissible time of exposure is reduced by 50%. The time-intensity exchange ratio is capped at 115 dB A-weighted, meaning that for any

[*]The A-weighted exposure limits have been criticized as improper for military exposures that are predominantly low frequency sounds (e.g., Burdick et al., 1978ab).

[†]It is recommended that peak sound pressure level dBP is measured using C-weighting to facilitate standardization of the frequency response of the measurement system (Johnson et al., 1998).

non-impulsive exposure that lasts less than one-quarter hour, the noise level must be less than 115 dB A-weighted. All continuous, intermittent, and impulsive noise between the levels of 80 and 130 dB A-weighted must be included in the exposure calculation (OSHA, 1981; 1983; NIOSH, 1998). If the TWA level exceeds 90 dB A-weighted the use of hearing protectors is mandatory. In the case of continuous noise, hearing protectors are selected on the basis of their noise reduction ratio (NRR) if the levels of noise are measured with C-weighting. If the levels of noise are measured as dB A-weighted, a correction factor of –7 dB is applied to the NRR value to account for uncertainty in the spectrum of the noise (Kroes, 1975). No guidance regarding the use of hearing protectors at peak pressure levels above 140 dBP is provided.

The cornerstone of all industrial hearing protection criteria proposed to date—except for the maximum peak sound pressure level at the ear—is the time-intensity exchange rate that specifies the duration of time a person can be exposed to noise levels exceeding the maximum daily exposure. The typical exchange ratio is based on halving the permissible exposure time for each 3-dB increase in continuous noise level although there are countries that use a 5-dB exchange ratio (e.g., Brazil, Chile, Israel, and some provinces and territories in Canada) (I-INCE, 1997; Johnson, 2000). In the United States, the use of the exchange ratio varies from 3 dB (Army, Air Force, Environmental Protection Agency [EPA], U.S. National Institute for Occupational Safety and Health [NIOSH]), through 4 dB (Navy), to 5 dB (OSHA, Mine Safety and Health Administration [MSHA]). The value of 3 dB in the time-intensity exchange rate is based on the equal-energy hypothesis and the value of 6 dB is based on the equal-pressure hypothesis applied to expected hearing impairment.

An alternative way to express maximum allowable exposure to noise is to state the maximum permissible hearing threshold shift due to exposure to noise. This concept is based on the fact that exposure to noise causes some Temporary Threshold Shift (TTS), which eventually becomes a Permanent Threshold Shift (PTS) if the exposure continues. However, an exposure to very high level impulse noise may immediately cause severe PTS and such effect is referred to as an acoustic trauma. In the United States, the acceptable hearing levels (HL) shifts proposed by CHABA (1965) in their continuous and intermittent exposure DRC were 10, 15, and 20 dB at 1, 2, and 3 kHz, respectively. These shifts were based on hearing level values originally considered acceptable for good speech perception (American National Standards Institute [ANSI], 1951). Later, this criterion was changed to 25 dB HL regardless of frequency (ANSI, 1969) and is maintained currently (e.g., DA, 1998; Kryter, 1998, NIOSH, 1998). Limiting exposure effects to respective TTS values should result in comparable or lower PTS over the working lifetime of an exposed person.

As described earlier, the focus of the OSHA standard is on continuous noise exposure and hearing damage accumulated during continuous daily exposure to such noise over a working lifetime. Except for setting a maximum permissible peak sound pressure level at 140 dBP, no language referring to the protection from acoustic trauma and permissible impulse noise exposure when hearing protectors are worn is included. The non-auditory effects of impulse

noise are not addressed at all. However, many weapons systems produce noise levels greater than 180 dBP and few, if any, produce noise level below 150 dBP at the ear of the shooter, which makes the standards such as OSHA unfit for military applications.

1.2 Early Criteria for Military Noise Limits

In order to avoid exposing Soldiers to excessive noise levels, the U.S. Army developed the first impulse noise standard called HEL[‡] Standard S-1-63(B)[§] (Chaillet and Garinther, 1965). The goal of this standard was to provide specific noise limits to Soldier system developers. This standard and subsequent research sponsored by the Army (e.g., Coles et al., 1968) led to the development of the event duration dependent impulse noise DRC by the National Research Council (CHABA, 1968) (see section 4.1). However, the noise standardization efforts by the U.S. Department of Labor (DL, 1969) and U.S. Army medical community (DA, 1972) setting a hard cap of 140 dBP on impulse noise exposure of the unprotected ear regardless of the number of impulses or impulse duration superseded CHABA's efforts to establish a DRC for impulse noise. As the result, the new version of HEL Standard S-1-63C (Garinther and Hodge, 1972) and the subsequent MIL-STD-1474, which adopted the HEL Standard S-1-63C requirements, while maintaining several original concepts, established the unprotected ear exposure at 140 dBP and abandoned the concept of an impulse-duration dependent DRC.

As its HEL predecessors, the U.S. Department of Defense Design Criteria Standard—Noise Control, commonly referred to as MIL-STD-1474, is a design guide for noise limits aimed primarily at weapons system designers. The latest version of the standard—version "D"—was published in 1997 (MIL-STD-1474D, 1997). The standard specifies permissible noise levels for effective speech communication and auditory detection considering human capabilities, the state of the art of noise reduction technologies, and existing U.S. government legislation. The standard also specifies absolute allowable noise levels under various listening condition. However, unlike OSHA, which combines exposure to steady-state and impulse noise into a single time-weighted average exposure, MIL-STD-1474D provides separate limits for both types of noise exposures and specifies a maximum allowable number of impulse exposures per day. According to MIL-STD-1474D, military personnel are required to wear hearing protection when the TWA level exceeds 85 dB A-weighted or when the maximum peak sound pressure exceeds 140 dBP. In another contrast to OSHA, the standard sets the limit on multiple daily exposures to impulse noise when hearing protectors are worn. The standard also sets a maximum permissible level of 155 dBP for non-auditory effects of noise set originally by CHABA (1968).

[‡]HEL refers to the former U.S. Army Human Engineering Laboratory, now part of the U.S. Army Research Laboratory.

[§]The initial version of the standard—version (A)—was presented at the national meetings but never formally published and was replaced after several months with version (B).

The limits of exposure set in the MIL-STD-1474D are absolute limits of zero risk of hearing damage that are established to protect the entire exposed population without providing any information about the probability of hearing damage when these limits are exceeded. However, in the absence of a suitable military-focused DRC, the MIL-STD-1474D standard has been used for several decades as a *de facto* DRC implying 95% probability of no hearing damage. While such an interpretation sets effective hearing protection criteria, newly researched information about the hearing damage caused by impulsive exposures has caused most stakeholders to view the MIL-STD-1474D DRC application as too conservative and as providing too severe a limit on weapon systems needed to ensure battlefield survivability and success. A more appropriate and effective hearing protection standard needs to take into consideration that "hearing protection protects better for impulse noise than for continuous noise" (Johnson et al., 1998, p. 85).

1.3 Military Noise Limits Criteria Now and in the Future

Military noise limits in the U.S. are defined by MIL-STD-1474D. The standard has been criticized for years as being too conservative with respect to impulse noise limits but none of the proposed alternatives received wide support in the research community.

The discussions about impulse noise limits resulted in an enormous literature database signified by seemingly incompatible data sets and contradictory views and interpretations. The database does not clearly resolve such basic issues as whether average energy or peak sound pressure should be used as a main criterion for the impulse DRC, whether impulse duration is important or not, whether shorter or longer impulses are more hazardous, whether earmuffs or earplugs are better protectors against impulse noise, or whether hearing protector attenuation is greater or smaller for impulse noise than for steady-state noise. Much of the controversy results from various definitions of the terms used to describe impulse noise or its measures but some of the differences in the data and opinions are clearly more fundamental. The lack of consistency in data and data interpretation lead to only one scientific conclusion—the complex physical processes of hearing damage are not simplistically caused by one or two individual quantities such as energy, peak pressure, pulse duration, earmuffs, or earplugs. Therefore, it is critically important that the future DRC and damage limits that need to be established for impulse noise effects are sufficiently sophisticated to be able to handle the variety of seemingly contradicting effects. Previous failed efforts to develop impulse noise limits encompassing all types of military impulses, hearing protectors, users, and operational situations clearly indicate that no future efforts leading to a single- or two-parameter criterion will be successful. The impulse noise effects are too complicated to be successfully described by such simplified metrics. Only criteria that take into account the entire exposure situation—the full impulse history—are able to be flexible and effective enough to successfully address the wide range of impulse exposures.

This report presents the current U.S. efforts in developing effective impulse noise limits that are acceptable to medical personnel, weapon designers, and military commanders; and discusses the relative advantages and disadvantages of various approaches proposed to date. The goal of the report is to justify the need for a new, state-of-the-art impulse noise DRC and identify the best available option.

2. Military Noise Exposure

2.1 Warfare: Survivability vs. Lethality

Western military doctrines revolve around two basic goals: elimination of the enemy forces and protection of friendly warfighters. Since the two opposing forces engaged in symmetric warfare have the same goal of destroying the enemy, this has historically led to the gradual but natural deployment of more powerful weapons. More powerful weapons result in increased exposure of the Soldiers to higher impulse noise levels caused by both friendly and enemy fire. This means that more powerful weapons require better ballistic protection as well as better protection of the Soldier's hearing from exposure to harmful high level impulse noises. Figure 1 graphically shows a notional battlespace of the 21st century in which Soldiers are exposed to noise coming from all the directions.

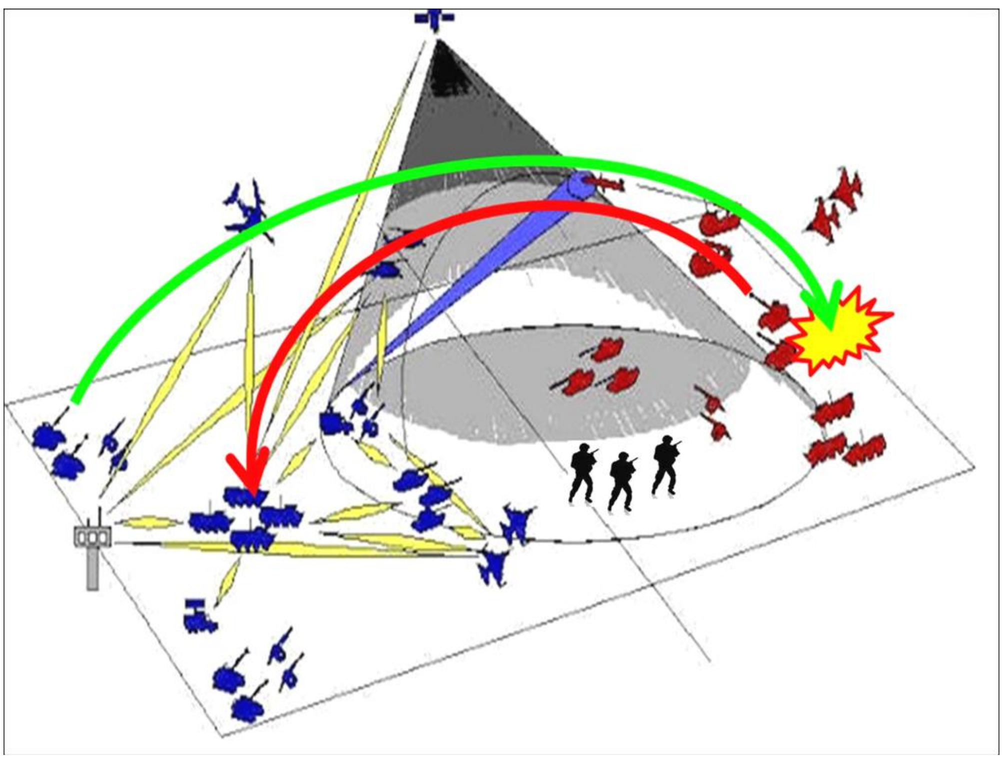

Figure 1. Twenty-first century battlespace—increased lethality involves launching more powerful projectiles for greater distances and with greater accuracy than the enemy. Modified version of a graphic retrieved on 7 April 2011, from http://www.ccii.co.za/products/iccs.html.

Protection of friendly troops is accomplished by providing the Soldiers with various forms of hearing protection devices and by setting limits on the impulse sounds produced by the power of their own weapons, since such weapons are the main source of hearing damaging noise. However, both enhanced hearing protection and weapon limitations come at significant costs. Hearing protection compromises auditory awareness of the environment and is detrimental to direct person-to-person speech communication. Limiting power of the weapons compromises Soldiers' lethality, increases the likelihood of friendly casualties, and also extends the duration of the conflict and the period of time during which Soldiers are exposed to other harmful noises and enemy action as well. While military planners and preventative medicine officers usually support both means of protection, field commanders, weapons systems developers, and front-line Soldiers are frequently against both, especially the latter. The need for a compromise is obvious but the place to draw the line is unclear.

The current U.S. Army solution provides some form of hearing protection permitting effective face-to-face speech communication by using level-dependent hearing protection. This form of hearing protection results in a minimal attenuation of sounds in quiet environments with increasing attenuation as the level of impulse noise increases. Existing level-dependent (nonlinear) hearing protection devices (HPDs) are not yet fully satisfactory but they offer promising improvements over current linear HPDs. In contrast, there is little progress in developing less noisy yet highly lethal explosives and weapons and effective, scientifically based guidelines regarding impulse noise limits. For the U.S. Army, weapons systems may not routinely be used operationally without compliance with general Health Hazard Assessment (HHA) criteria. This mandated review evaluates 11 different health or safety risks associated with each system including acoustic energy, which may interact with the body to cause hearing loss or damage to internal organs (DoD, 2007). The acoustic energy limits used in HHA criteria are based on the MIL-STD-1474D (1997). This document was a major accomplishment at the time of its creation but its recommendations are based on currently outdated knowledge about the human auditory system and outdated impulse noise measurement techniques. Based on our current knowledge, the noise limits for impulse noise that are established in this standard are very conservative and based on inadequate biomedical data and a number of not confirmed assumptions (Leibrecht et al., 1987). Thus, the widespread acceptance of the standard's limitations and the lack of scientifically based supporting evidence suggest that the existing noise limits are not aligned with the actual hearing threat caused by various weapon systems (e.g., Chan et al., 2001; Patterson and Johnson, 1996ab). Therefore, without an effective military-based DRC, more powerful and effective weapons systems are likely to be kept out of Soldiers' hands, which may endanger them to a much greater extent than exposure to noise levels too conservatively thought to be dangerous. As the result, the use of newly developed safe, effective, and lethal weapons systems may be prohibited due to the lack of an appropriate DRC designed specifically to address the high impulsive noise levels associated with military weapons.

2.2 Weapon Sounds Characteristics

2.2.1 Sound Level

The U.S. Army and military units worldwide depend greatly upon their long range weapon systems capable of delivering lethal ordnance to targets at greater distances than the adversary's weapons. This quest for increased lethality and maximum engagement distance extends to all types of projectile-based weapons systems including direct-fire weapons and indirect-fire weapons, such as mortars and rockets. The former systems range from small arms rifles and pistols, through shoulder-fired recoilless weapons, to crew-served systems varying from 0.50 cal. through 127-mm shoulder-fired missiles. This desired superiority does not come hazard-free. Maximizing a weapon's lethality requires increased interior guntube pressures, higher muzzle velocities, and more rearward-deflecting muzzle brakes—all of which cause increased sound pressure levels at the operators' positions. The peak sound pressure levels produced by several existing U.S. weapon systems are listed in table 1. The listed levels are the average levels while actual levels may vary considerably depending on the weapon charge, weapon condition, and environmental factors.

Table 1. Peak sound pressure levels (dBP) of U.S. weapons systems (North Atlantic Treaty Organization [NATO], 2010).

System	Caliber (mm)	Description	Location	Sound Level
MK19 (Mod 3)	40 mm	Grenade launcher	Gunner	145
M2	0.50 cal.	Machine gun	Gunner	153
M60	7.62 mm	Machine gun	Gunner	155
M16A2	5.56 mm	Rifle	Shooter	157
M9	9 mm	Pistol	Shooter	157
M249	5.56 mm	Squad automatic weapon	Gunner	159.5
JAVELIN	127 mm	Guided missile	Gunner (open)	159.9
M26 (not the current M26 MASS)	N/A	Grenade	at 50 ft (15.24 m)	164.3
JAVELIN	127 mm	Guided missile	Gunner (fighting)	172.3
M72A2	66 mm	Light antitank weapon	Gunner	182
M119	105 mm	Towed howitzer (charge 8)	Gunner	183
M224	60 mm	Mortar (M888 round, charge)	0.5 m from muzzle	185
M3	84 mm	Multi-role Anti-armor Antipersonnel Weapon System (MAAWS) recoilless rifle	Gunner	190

Note: N/A = not applicable.

Sound energy may be quantified in various ways including: root-mean-squared (RMS), the effective sound pressure expressed as the square root of the time-averaged, squared sound pressure; or the equivalent continuous sound pressure level (commonly referred to as L_{eq}), an imaginary continuous signal, over a given time interval (usually 8-h), which would produce the same energy as the specific sound level being represented. Figure 2 clearly shows the lowest impulse sound level of military weapons systems (peak value, dBP) far exceeds the human

threshold of pain and is much higher than steady-state sounds (RMS value, dB A-weighted) found in both civilian and military environments.

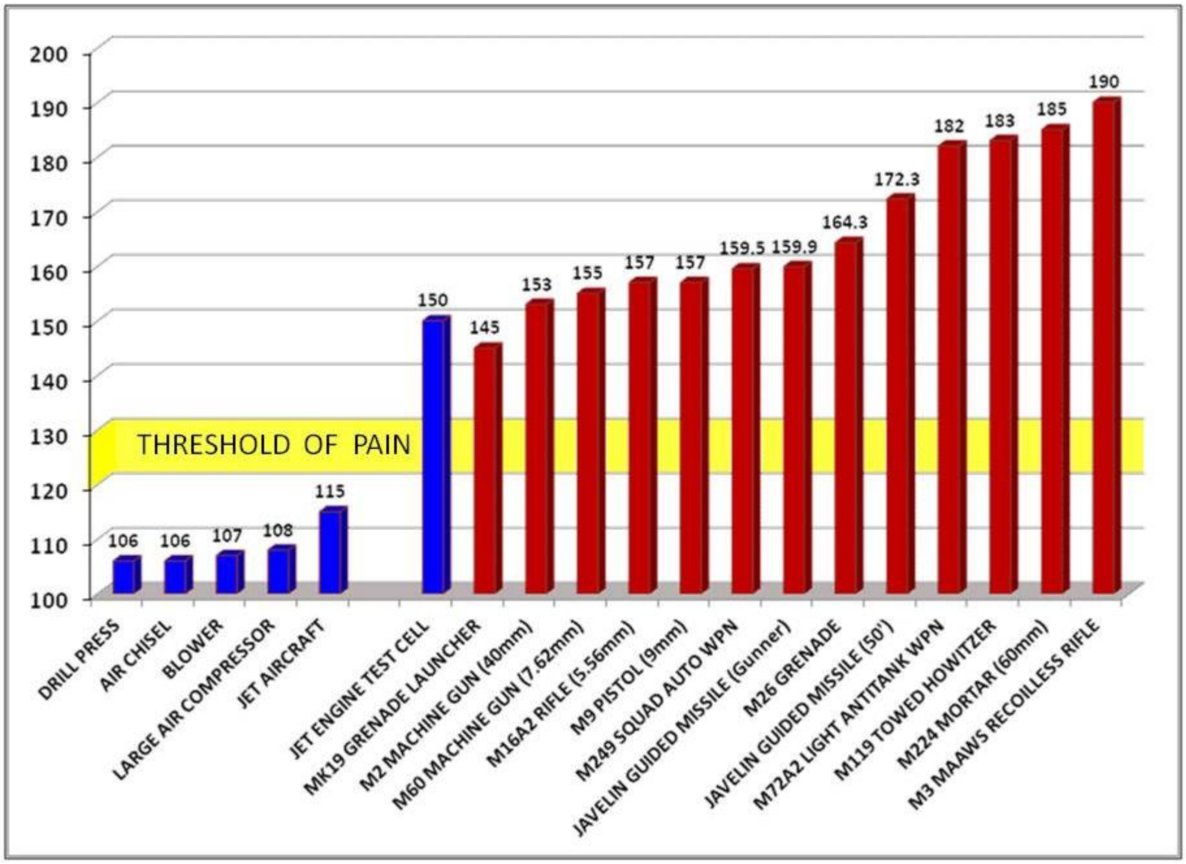

Figure 2. Peak impulse noise levels (dBP; red bars) produced by military weapons systems far exceed most of the continuous levels of sounds (dB A-weighted; blue bars) found in both civilian and military environments.

Regarding the acoustic spectra of impulse noises, the sounds produced by large-caliber weapons have acoustic energy predominantly concentrated in the low frequency region (below 400 Hz with a peak in the 16–100 Hz range), while the spectral content of sounds produced by personal weapons (rifles and pistols) extends from about 150 to 1500 Hz with a concentration of acoustic energy around 1000–1500 Hz (Ylikoski et al., 1995).

Since it is sometimes difficult to determine if a specific signal can be classified as an impulse despite its short duration, Starck and Pekkarinen (1987) proposed to define the impulse as the signal which meets the following crest factor criterion:

$$I = L_p - L_S \geq 15 \text{ dB}, \quad (1)$$

where I is impulsiveness (a.k.a. crest factor) of a given sound, L_p is the A-weighted peak level and L_S is A-weighted RMS level measured with slow time constant. In the United States, some attempts have been made to quantify "impulsiveness" of sound by calculating kurtosis of the ongoing sound (Hamernik et al., 2003), but this criterion has yet to be made applicable to military exposures.

2.2.2 Temporal Characteristics

Estimating the hearing hazard of weapons firing is difficult and has been the subject of discussion for decades. The peak sound pressure levels listed in table 1 are just one of several characteristics of the muzzle blast that contribute to noise hazard. Each weapon, when fired under specific conditions, generates a unique signature that not only varies in peak pressure but also in time history and spectral content. Some examples of weapon impulse noise waveforms are shown in figure 3. As can be seen, peak pressures, number and type of zero crossings, and durations of various parts of impulse waveforms vary considerably between weapons and within the same weapon as firing conditions are varied. All these parameters, as well as overall energy, contribute to noise hazard (Price, 2008; Price, 2007a; Kardous et al., 2005).

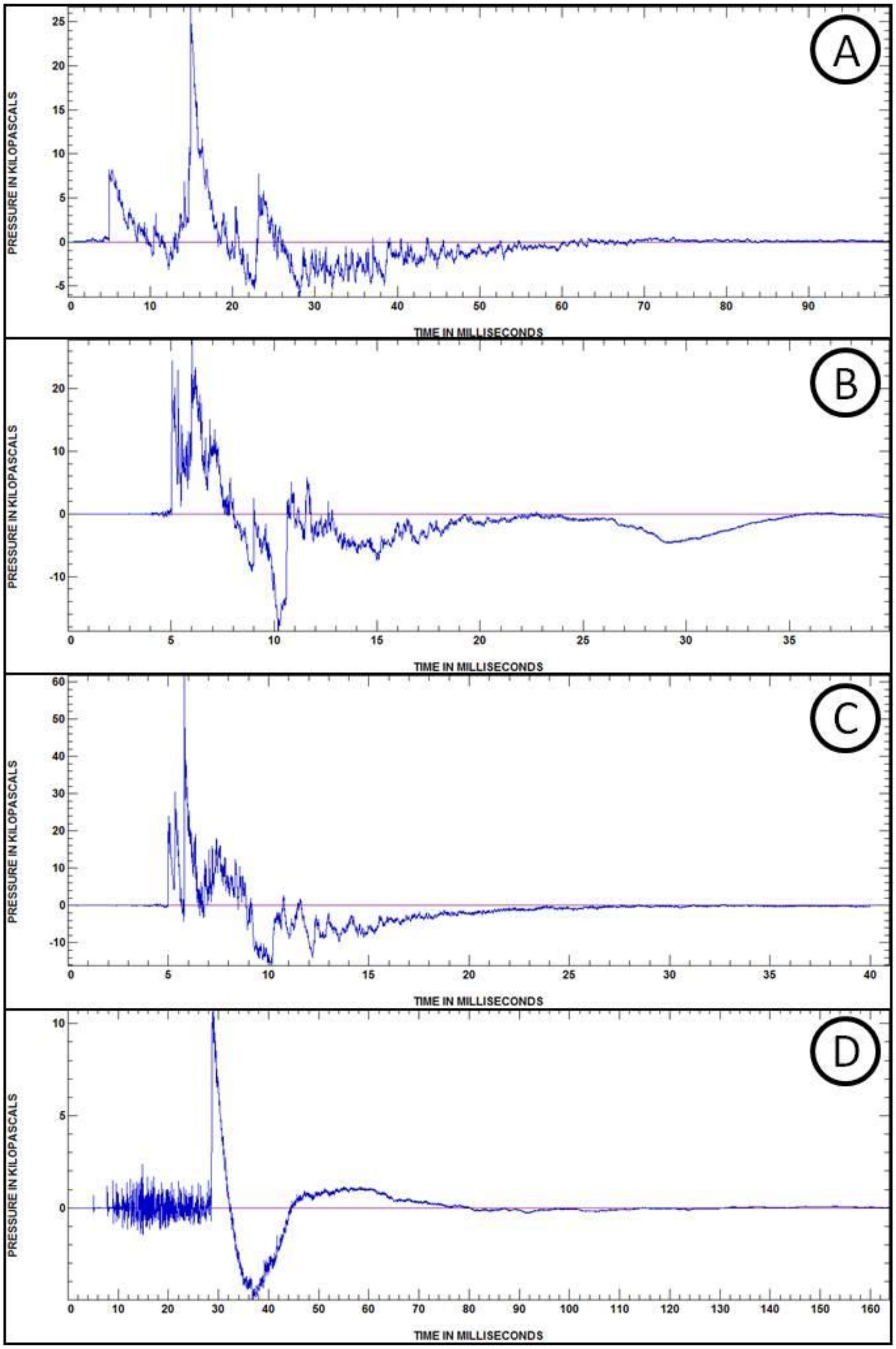

Figure 3. Waveforms of weapon sounds: panel A: artillery round (charge 3), panel B: antitank rocket (standing), panel C: antitank rocket (kneeling), and panel D: mine clearing charge (Amrein and Letowski, 2011).

The rise time of the initial peak of the weapon fire impulse is very short and typically below 4 μs (e.g., Becker, 1922). The length of the positive phase of the sound pressure waveform is of the order of 0.1–5 ms and is usually much shorter than the duration of the negative phase. However, the overall length of the impulse depends on how the duration of the event is defined. There are four basic concepts of impulse sound duration used in noise hazard literature. These durations are referred to as durations A, B, C, and D. The concepts of these durations are shown in figure 4 and are discussed further in sections 4.3 and 4.4.1.

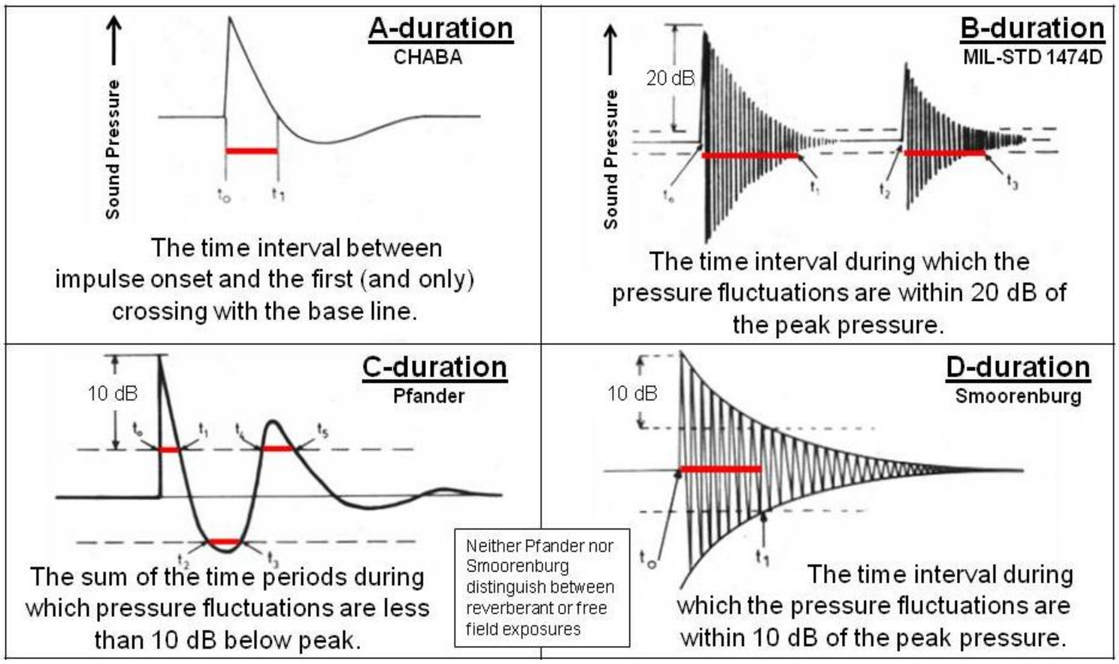

Figure 4. Definitions of impulse duration used in noise hazard calculations (NATO, 2003).

2.3 A Case Study

Some types of impulse noises encountered within the military are so intense that a single impulse arriving at the unprotected ears could result in severe permanent hearing loss even when the impulse is very short and contains little energy (Ades et al., 1955). For example, as reported by Vause and LaRue (2001), a U.S. Soldier in training fired an M136 AT4, an anti-tank weapon, which is an 84-mm unguided, portable, single-shot recoilless smoothbore weapon built in Sweden by Saab Bofors Dynamics (shown in figure 5). The weapon produces an impulse noise of 185 dBP with a pulse duration of 2.3 ms at the ear of the shooter (Vause and LaRue, 2001). This particular Soldier fired the weapon without wearing any type of hearing protection. As can be seen in figure 5, his normal hearing was immediately severely degraded and he became a casualty. Thirty-days after the event, his hearing remained severely impaired and he was removed from the military service due to his injury. While this is a severe example of non-compliance, it reinforces the need for a proper DRC and administrative and engineering controls to prevent such events from reducing the effectiveness of our forces and incapacitating our

Soldiers for the remainder of their lives. This example also emphasizes the devastating hazard potential of the peak sound pressure even when the total energy of the signal is relatively small.

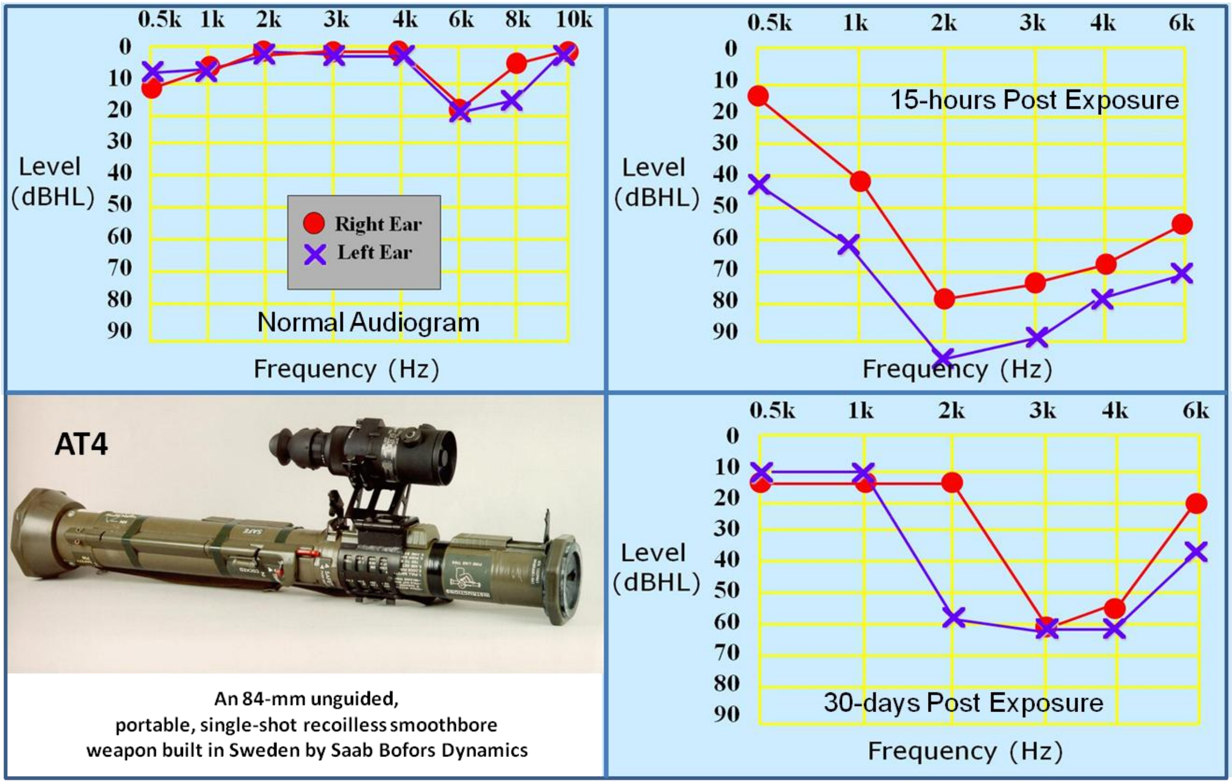

Figure 5. A case study: Ft. Bragg Soldier—AT4: one exposure, no hearing protection.

3. Mechanisms of Hearing Protection

The primary hearing loss mechanisms are intracochlear and result from mechanical stress within the organ of Corti. At high sound input levels, the conductive path to the cochlea exhibits spectral tuning, transmission attenuation from middle ear muscles, and displacement peak limitations of the stapes. All of these components contribute to the nonlinearity of the human ear. It is this nonlinearity that protects humans from catastrophic failure when exposed to high level impulse noise. Likewise, external nonlinear hearing protection can extend the inherent nonlinearity of the human ear to permit safe exposure to even higher levels of impulsive noise.

3.1 Human Ear

3.1.1 Physiology of Hearing

An auditory signal arriving at the human ear is processed by mechanical structures of the outer and middle ears and converted into a neural response at the organ of Corti located in the cochlea of the inner ear. The role of the outer ear is to filter the incoming signal to encode directional

information carried by the signal and equalize spectral properties of the signal to improve auditory perception in frequency regions critical for perception of ecologically important sounds. Such a processed signal impinges on the tympanic membrane separating the outer ear from the middle ear. Vibrations of the tympanic membrane are transmitted through a connected chain of three small bones (malleus, incus, and stapes), called ossicles, to the oval window of the inner ear that is driven by a footplate of the stapes. Both outer and middle ears are air-filled cavities while the inner ear is filled with a fluid. The role of the middle ear structures is to compensate for the signal loss due to a mismatch between the impedance of air and the impedance of fluid in the inner ear. The oval window is the entry point to the cochlea of the inner ear. The cochlea is a fluid-filled snail-like membranous sack divided along its whole length into two parallel channels, scala tympani and scala vestibule, by a membrane called the basilar membrane. The basilar membrane is the support structure for the organ of Corti distributed along all its length. The oval window opens into the scala vestibuli and the vibrations of the stapes push the inner ear fluid along the length of the basilar membrane and through a small opening (helicotrema) at the end (apex) of the cochlea into the scala tympani terminated with another window (round window) that opens back into middle ear cavity. The movement of the fluid being pushed back and forth between the scala vestibule and scala tympani vibrates the basilar membrane and the attached organ of Corti. Mechanical vibrations of the organ of Corti result in biochemical processes in the hair cells of the organ of Corti that are the actual organ of hearing. Biochemical changes in the hair cells are the source of neural impulses that are transmitted from the cochlea to the brain through a strand of neural fibers called the auditory nerve and are interpreted by the brain as auditory sensations resulting from external acoustic stimulation.

3.1.2 Protective Mechanisms of Human Ear

The hair cells of the organ of Corti are very delicate structures and overstimulation can permanently damage them resulting in non-recoverable hearing loss. In order to protect the organ of Corti against excessive acoustic stimulation, the transmission system of the human ear incorporates several protective mechanisms (negative feedback systems). The two most important protective mechanisms are the acoustic reflex and the nonlinear behavior of the stapes driving the oval window of the cochlea.

3.1.2.1 Acoustic Reflex

Acoustic reflex (AR) is an involuntary contraction of the middle ear muscles in response to high intensity acoustic stimulus. The ossicular chain of the middle ear, transmitting acoustic stimulus from the tympanic membrane to the oval window, is supported and sustained by two middle ear muscles: tensor tympani and stapedius. The tensor tympani muscle is about 25 mm long and is attached to the manubrium of malleus, which is connected directly to the tympanic membrane, and its contraction pulls the malleus inward and increases the tension of the tympanic membrane (Rodriguez-Velasquez et al., 1998). The stapedius muscle, the smallest muscle in the human body with length of about 6 mm, is connected to the stapes and its contraction pulls the stapes

away from the oval window, which reduces the range of motion of the stapes (Djupesland and Zwislocki, 1971; Zwislocki, 2002). Both of these fairly simultaneous actions increase the stiffness of the ossicular chain, resulting in the decrease of the amount of force driving the oval window (Bermejo, 2004; Møller, 1972; Misurya, 1976). An important property of the middle ear muscles is that they have both ipsilateral and contralateral projections. As a result the AR is a bilateral effect, which means, that the left and right ear muscles contract together in response to high intensity sound in either ear[**] (Lüscher, 1929; Borg, 1973; Gelfand, 1984; Emanuel and Letowski, 2009).

The lowest intensity acoustic stimulus that triggers the AR is called the AR threshold. The threshold level depends on the person and the type of stimulus but normally it falls in the 60–80-dB sound pressure level (SPL) range for noise-like stimuli and in the 80–100 dB SPL range for pure tone stimuli (Jepsen, 1963; Gelfand, 1984; Lass and Woodford, 2007).

The force of contraction of the AR increases with increasing intensity of the acoustic stimulus, but only up to the intensities about 20–30 dB higher than the reflex threshold (Dallos, 1964; 1973) and it decreases with age (Jepsen, 1963). The fact that AR reaches its maximum at 20–30 dB above AR thresholds indicates that sound pressure levels of 100–110-dB SPL invoke the maximum response from the AR system and further increase in stimulus level does not affect it. The latency (time delay) of the AR reported in literature ranges from 10 to 150 ms for stapedius contraction and from 10 to 290 ms for tensor tympani contraction, and depends on the intensity and frequency of the stimulus (Solomon and Starr, 1963; Loth et al., 1987; Møller, 2000; Lass and Woodford, 2007). Average latency times calculated by Wever and Lawrence (1954) are 60 ms for the stapedius and 150 ms for the tensor tympani. Decay (relaxation) time of the AR also varies greatly and ranges from 200 μs to 1–2 s (Sulkowski, 1980). Due to the typically long latency and relaxation times of the AR, such a protective mechanism can only operate in the low frequency range (below 1–2 kHz) and for stimuli that have a sufficiently long duration (Zakrisson, 1975). At low frequency range, the contractions of the middle ear muscles provide up to 10–20 dB effective attenuation of the transmitted stimulus but the attenuation can be as low as a few dB or 0 at higher frequencies (Borg, 1968; Brask, 1979; Simmons, 1959; Sulkowski, 1980; Pang and Peake, 1986; Lass and Woodford, 2007). In addition, even at low frequencies, muscle contractions do not last indefinitely and the muscles quickly adapt to high intensity sounds and cease contracting indicating that AR can only operate on short-term basis (Lüscher, 1929; Tonndorf, 1976; Dancer, 2004).

3.1.2.2 Warned and Unwarned Response of the Ear

The role of the AR in protecting hearing against impulse sounds has been discussed for decades (Colletti et al., 1992). Based on the long time constants of the AR, it is generally assumed that this mechanism cannot provide substantive protection against noise impulses, such as sounds

[**]The ipsilateral threshold is usually 2–5 dB lower (Wiley et al., 1987).

produced by firearms and explosions, which are very short events (Sułkowski, 1980). However, it has been observed that contraction of the middle ear muscles can happen prior to occurrence of impulse noise if such noise had been expected (Marshall and Brandt, 1974; Dancer, 2004). Price (2007a) refers to human reaction to unexpected and expected sounds as the *unwarned response* and *warned response*. The expected occurrence of a noise impulse is much safer for the hearing organ (warned response) than the unexpected event (unwarned response). This difference in human reaction may be caused not only by the anticipatory contraction of the middle ear muscles but also by lower general physiological stress within the auditory system. For example, an extreme unwarned response, the startle response, is characterized by vasoconstriction and sudden increase in blood pressure that can affect the biochemistry of the organ of Corti.

The AR does not only react to high noise levels and anticipation of a high noise event, but it also can be invoked by vocalization (e.g., coughing or humming) or even by chewing or mouth opening regardless of the presence or absence of high level impulse noise. In addition, there are some data indicating that temporarily disabling AR results in an increase in the amount of temporary hearing loss in the 4-kHz region produced by a given sound insult (Nilsson et al., 1980; Zakrisson et al., 1980). One explanation of this effect is multimodal middle ear muscle activity suggested by Simmons (1959). According to this concept, after arriving at the ear, any stimulus having sufficiently long rise time induces spontaneous fluctuations in muscle activity, which may be sufficient to detune the middle ear's antiresonance at 4000 Hz and thus average out its effect (Dallos, 1973). The other modes are skeletal muscle activity mode (e.g., in response to chewing) and an external overstimulation protection mode. This suggests that "even though the attenuation provided by the AR is primarily in the low frequencies, the AR can also decrease the risk of damage at high frequencies" (Colletti et al., 1992, p. 501). Other studies have also shown that changes in the stimulus properties over time, such as impulse noises embedded in steady-state noise, may prevent the decay of the AR, thereby increasing its effectiveness (Borg et al., 1979; Lutman and Martin, 1978). All these data seem to support the notion that the AR may play a role in protecting hearing against damage caused by both continuous noise and repetitive impulsive sounds (e.g., series of weapon fires arriving in rapid succession), resulting in a warned response of the auditory system (Price, 2007a).

3.1.2.3 Nonlinear Mechanism of Stapes

The other hearing protection mechanism operating in the middle ear is the nonlinear behavior of the annular ligament of the stapes. This mechanism was discovered by Békésy (1936) who observed that when low-frequency ear stimulation increases above a certain point the axis of stapes rotation changes (see also Kirikae, 1960). As a result of this change the *piston-like movements* of the stapes are replaced by a *tilting action*, which is much less effective in pushing cochlear fluids back and forth (Høgmoen and Gundersen, 1977). Price (1974) described this protective mechanism as *peak clipping* response of the stapes.

3.1.2.4 Efferent Neural Pathways

In addition to two negative feedback mechanisms of the middle ear there is an additional protective mechanism in the inner ear controlled by the efferent neural system. Each hair cell of the organ of Corti has synaptic connections with *afferent nerve fibers* transmitting a neural response of the hair cell to the brain and with *efferent nerve fibers* delivering control signals from the brain. One of the roles of the efferent system is to reduce the dynamic range of the afferent system in case of overstimulation of the hair cells to prevent their damage. As such, the efferent system seems to be involved in protecting the auditory system against both temporary and permanent hearing loss (Rajan, 1988; Henderson et al., 2001; Maison and Liberman, 2000). This system has been referred to by Dancer (2004) as the *inner ear acoustic reflex*. Although the latency of the efferent feedback system is relatively long (20–100 ms) and its effectiveness in protecting the auditory system from damage made by single isolated impulses is quite limited, it may provide better protection than the contraction of the middle ear muscles in the high frequency region by acting directly on hair cells sensitive to high frequency stimulation. Both middle and inner ear protective mechanisms seem, however, equally effective in protecting auditory system against the bursts of impulses (Dancer, 2004).

3.2 Pharmacological Intervention

As mentioned before, the source of the auditory response to acoustic stimulation are degenerative biochemical processes within the organ of Corti including antioxidant depletion and hemoglobin (Hb) oxidation (Armstrong et al., 1998). Therefore, one additional potential course of action to prevent hearing loss from excessive stimulation is to pharmacologically affect these processes by increasing the antioxidant stress on the hair cells prior to, or immediately after, exposure to noise. Results of a number of animal studies demonstrated the effectiveness of antioxidant drugs injected into cochlea on the reduction of hearing loss caused by subsequent exposure to noise (e.g., Kopke et al., 2001). However, in the case of people, orally administered L-N-acetylcysteine, D-methionine, lipoic acid, and vitamin E demonstrated positive effects in preventing hearing loss (Armstrong et al., 1998; Dancer, 2004; Kopke, 2005). Similar drugs also can be used in reducing the effects of auditory overstimulation (Kopke et al., 2001). However, different therapy may be needed to recover from metabolic exhaustion or cellular disruption (Price, 2007a). In addition, gradually increasing exposure to high noise levels enhances tolerance to noise and can be implemented in a form of preconditioning to decrease the amount of hearing loss caused by acoustic trauma (Niu and Canlon, 2002; Dancer, 2004).

3.3 Hearing Protection Devices

3.3.1 Linear Hearing Protectors

Both earmuff-type and earplug-type HPDs provide relatively high attenuation of high frequencies. This adversely affects speech communication in quiet and in low levels of noise. Generally, all passive linear HPDs interfere with speech communication and prevent detection of

low-level sounds in the surrounding environment, thereby compromising auditory situation awareness. This deficiency is addressed by different types of level-dependent HPDs. Level-dependent HPDs are nonlinear HPDs that significantly attenuate hazardous high intensity impulse sounds while minimally attenuating low intensity sounds such as conversational speech. Level-dependent reduction of noise levels can be achieved by either passive or active reduction techniques.

3.3.2 Passive Nonlinear Hearing Protectors

Passive nonlinear (level dependent) HPDs are non-powered vented devices with small orifices, diaphragms, or valves built into the HPD. These increase the protection provided against impulse noise as the noise level exceeds a pre-set threshold, usually 120 dB SPL (Shaw, 1982). Above this threshold, high noise levels result in a turbulent flow of air through the nonlinear element of the protector, effectively dissipating the acoustic energy and preventing its transport beyond the vent. Below this threshold, the protector acts as a regular vented HPD usually providing less than 20 dB of noise attenuation at high frequencies and very little attenuation at low and middle frequencies below 1000 Hz (normally less than 5 dB below 500 Hz). Such protection characteristics of level-dependent HPDs facilitate speech communication and improve awareness of the environmental sounds in quiet and moderately noisy environments while protecting the user from high intensity impulse sounds from their own and enemy weapons fire.

The Combat Arms Earplug (CAE) is an example[††] of a level-dependent passive device designed for military operations. The earplug is produced in both single-end and dual-end versions shown in figure 6. The dual-end version can be used as either a linear (green plug) or nonlinear (yellow plug) HPD. A small mechanical filter with a calibrated orifice is embedded in the nonlinear end of the plug. When this end is inserted into the ear canal, the CAE passes the low-intensity, low-frequency sounds with as little as 5–8 dB attenuation and allows the user to hear normal conversation, footsteps, or vehicle noise while to some degree attenuating high frequency energy of the sounds.

The attenuation of the CAE rapidly increases at high noise levels starting at ~120 dBP SPL and reaches full peak attenuation of 25 dB at ~190 dBP (Dancer and Hamery, 1998), providing wideband hearing protection against the dangerous high-level energy of weapons fire and explosives. The linear portion of the CAE is used for hearing protection from high level steady-state noise environments such as those created by armored vehicles or aircraft where situation awareness is not a priority. It provides ~35-dB insertion loss at low and middle frequencies with insertion loss gradually increasing above 1000 Hz. At very high sound intensity levels exceeding 170 dB (peak), both types of the CAE earplug provide similar attenuation for frequencies above 250 Hz.

[††]Other examples include Health Enterprises ACU-LIFE Shooter’s Ear Plugs (Sonic Valve II) and SureFire EP3 Noise Defender.

Figure 6. CAE: dual-end version (left) and current single-end version (right) (U.S. Army Research Laboratory photos).

3.3.3 Active Nonlinear Hearing Protectors

Another class of nonlinear hearing protectors is Active Noise Reduction (ANR) devices. ANR is an electronic method of reducing the level of environmental noise by phase cancellation. In the ANR system, an environmental microphone monitors the surrounding noise, which is reversed in phase and presented back to the listener in an attempt to reduce the overall noise level. A general concept of an ANR system is shown in figure 7, where environmental noise is monitored by the external noise reference microphone mounted outside of the passive HPD system. Captured noise is reversed in phase, signal processed, and emitted under the HPD by an audio transmitter. The internal error microphone located close to the entrance to the ear canal monitors the overall noise level under the earmuff and provides a differential signal that controls the amount of out-of-phase noise required to minimize the overall noise level. Systems using ANR are frequently referred to as noise cancelling earphones or active noise-cancelling earphones. (Tran et al., 2009)

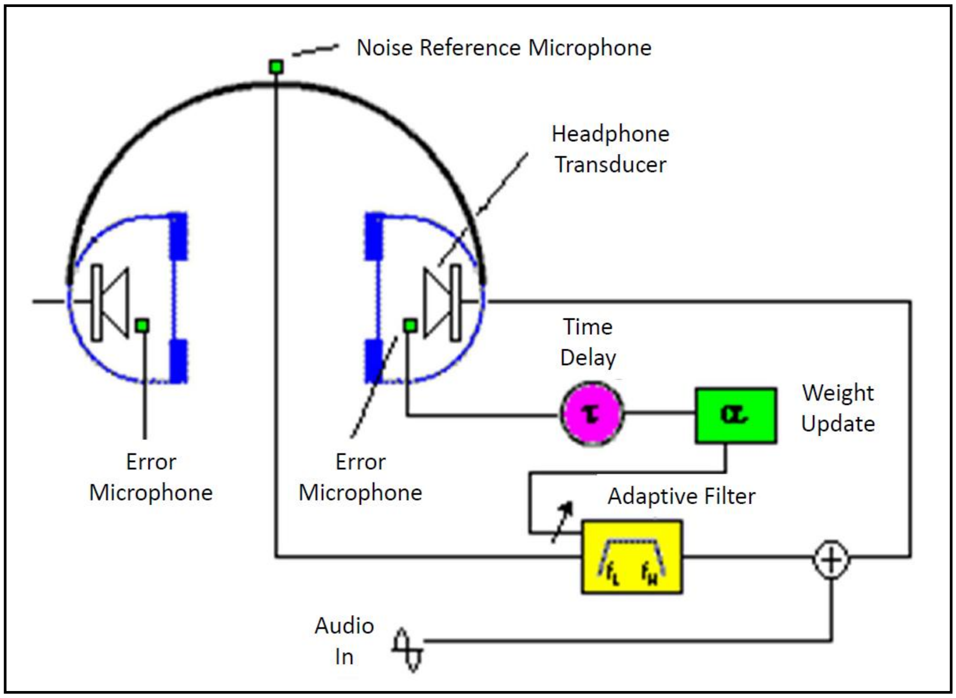

Figure 7. ANR system incorporated in an audio HMD (Moy, 2001).

4. Hearing Loss Assessment Criteria for Impulse Noise

4.1 The Concept of Damage Risk Criteria

The term DRC refers to the risk of health hazard caused by noise exposures in a fraction of the exposed population over the lifetime of the exposed person. The concept of a DRC applies to both continuous and impulse noise exposures. Although this term is quite common, it is not universal and has the same or similar meaning as Noise Exposure Limits (NEL), Hazardous Noise Limits (HNL), and the Hearing Conservation Criteria (HCC), in the case of hearing only. The DRC should not be confused with permissible exposure limits, although they are the basis for them (e.g., von Gierke and Johnson, 1976). The noise limits imposed by a DRC refer, in general, to the level of noise which actually enters the ear of the exposed person (Hodge and Garinther, 1973). However, if the noise levels exceed the DRC limits, these levels can be reduced by various means, such as hearing protectors, to or below the required limits. If the hearing protectors are used, these limits apply to the sound pressure level under the protector.

Most commonly, the health hazard caused by noise exposure is the immediate (acoustic trauma) or progressive (TTS and PTS) hearing damage to the sense of hearing and the relevant DRC are frequently referred to as an auditory DRC or a hearing DRC. However, exposure to blast energy may also affect organs other than hearing and a general DRC dealing with such energy must take into consideration injury to organs such as the lungs and upper respiratory tract (larynx, pharynx,

and trachea). Legislation issued in some countries (e.g., EEC, 1986; UVV Lärm, 1990) reflects the need for protecting people from non-auditory effects of noise exposure but no precise safe levels are recommended due to insufficient scientific knowledge of the non-auditory effects. In general, to avoid acoustic trauma and non-auditory injuries, the acoustic pressure must not exceed 5 psi to avoid eardrum rupture in the case of unprotected ears and 10 psi to avoid lung and other non-auditory injuries in the case of protected ears (Bowen et al., 1968; Hodge and Garinther, 1973). For the U.S. Army, the Office of the Surgeon General has adopted the exposure level of 155 dB, corresponding to the Z-curve in MIL-STD-1474D (see section 4.3), as the exposure limit for non-auditory blast injury (Richmond et al., 1982).

The hearing DRC should specify the recommended maximum noise levels for a given type of noise, duration exposure, and the probability of a specific type of hearing injury caused by this type of noise exposure (e.g., Ahroon et al., 2011). Such a meaning of DRC takes into consideration the fact that people differ in their susceptibility to noise and this susceptibility is further affected by operational conditions. The selected limit of noise exposure depends on the degree of hearing to be preserved and the percentage of the exposed population to be protected and this limit must be based on social and humane values (Eldredge, 1976). The most common protective goal of DRC is to preserve speech perception (hearing and understanding). Based on a review of several studies and recommendations CHABA originally adopted hearing levels of 10 dB at 1000 Hz and below, 15 dB at 2000 Hz, and 20 dB at and above 3000 Hz as a criterion for material impairment of hearing for speech (CHABA, 1965; Kryter et al., 1966). This criterion was later changed to an average hearing level of 25 dB across the 1000–3000 Hz region bilaterally regardless of the loss at each specific frequency (NIOSH, 1972; OSHA, 1981). The difference of about 10-dB HL between both sets of criteria is the result of about 10-dB difference in the standardized hearing threshold (audiometric zero) between the American Standards Association (ASA) (1951) and ANSI (1961) standards that were used as reference documents in determining CHABA and NIOSH criteria, respectively.

4.2 CHABA Damage Risk Criteria

CHABA (1965; see also Kryter et al., 1966) accepted the ANSI fence for acceptable PTS and further assumed that such PTS can be developed in no more than 50% of the people if the TTS measured at each of the above frequencies 2 min after the end of single day's noise exposure does not exceed 10, 15, and 20 dB, respectively. This assumption was made on the bases developed by CHABA (1965, table 1) estimating percentages of people with presumed PTS exceeding material impairment of hearing for speech after many years exposure to noise reported by Nixon and Glorig (1961) and Rudmose (1957). The CHABA's table 1 is shown here as table 2. In the case of continuous noise exposure, this set of criteria led to an average daily dosage of noise to be kept below 90 dB A-weighted across an 8 h work day. The realism of this limit has been confirmed by the future studies. For example, according to the paper published by von Gierke and Johnston (1976), the 5-dB noise-induced PTS limit requires the TWA exposure

below 84 dB A-weighted and protection of 90% of the population requires the TWA of less than 87 dB A-weighted.

Table 2. Estimated PTS at 1000, 2000, and 3000 Hz developed after many years of exposure to noise as a function of the fraction of the exposed population complying with the CHABA DRC.

Frequency	**Percentage of Exposed**		
(Hertz)	**50%**	**20%**	**10%**
1000	10 dB	20 dB	30 dB
2000	15 dB	30 dB	45 dB
3000	20 dB	40 dB	60 dB

The impulse noise DRC proposed by CHABA (1968) set the exposure limits for 100 impulses arriving at normal incidence in a time period of 4 min to 8 h during the day. The proposed impulse noise criteria assume the same TTS limits as the previously proposed continuous noise DRC (CHABA, 1965). The common intent of both DRCs is to protect 95% of the exposed population from material hearing loss for speech. With this criterion in mind, the maximum peak sound pressure level permitted without any hearing protection is set in the impulse noise DRC at 164 dBP for the reference impulse of negligible duration (25 μs). As B-duration of the impulse (see section 2.2.2) increases, the permissible peak sound pressure level decreases linearly with the rate of 2 dB for each doubling of duration reaching a plateau of 138 dBP for a B-duration exceeding 200 ms. The same applies to A-duration (see section 2.2.2) except that the terminal level of 152 dBP is reached at about 1.5 ms. For duration exceeding 1 s, the DRC for continuous noise exposure apply (CHABA, 1965; Kryter et al., 1966). If the impulses arrive at grazing rather than normal incidence the DRC are shifted upwards 5 dB. If the number of impulses in an *exposure period* exceeds 100 an additional decrease of permissible peak sound pressure level by 5 dB for each tenfold change in number of impulses is added.

The basic criteria of CHABA's (1968) DRC[‡‡] proposed for impulse noise are a 10-dB more restrictive version of the DRC proposed by Coles et al. (1968) in an attempt to (1) address normal rather than grazing incidence of noise impulse and (2) protect 95% of the population rather than 75% suggested by Coles et al. (1968). However, regardless of the proposed specific limits or protection goals, no formal impulse noise DRC has ever been implemented by the U.S. Military. The only formal criterion used in both industry and military standardization documents is the maximum permissible peak sound pressure level of 140 dBP for the unprotected ear. This level has been accepted on the basis of the report by Kryter et al. (1966) but "this number was little more than a guess when it was first proposed" (Ward, 1986). In this context, another impulse noise level DRC developed by Linag Zhian et al. (1983) should be mentioned.

[‡‡]While highly publicized in the literature, the CHABA (1968) recommendations have not been accepted by any U.S. regulatory agency.

According to this criterion the maximum permissible peak sound pressure level should be calculated as

$$P = 177 - 6 \log (T_A N) , \qquad (2)$$

where P is the maximum peak sound pressure, T_A is the duration of the positive pulse of the impulse (A-duration), and N is the number of impulses per day. As per the authors' claim based on a large number of experimental data, such maximum peak sound pressure level is efficient in protecting 90% of the exposed people from standard threshold shift. These levels are even less restrictive than the impulse noise DRC proposed by CHABA (1968).

4.3 Impulse Noise Criteria in MIL-STD-1474D

Requirement 4 of the MIL-STD-1474D specifies impulse noise limits based on the peak pressure and "B-duration" of the free-field waveform. These impulse noise limits are based loosely on CHABA's (1968) relation between level of the impulse and number of permitted impulses adjusted to accept the use of single hearing protection (29 dB attenuation) and double hearing protection (29 + 6.51 dB). Therefore, they can be interpreted as a 95% DRC. The 140-dBP level constitutes a hard cap for noise exposure by the unprotected ear. Based on these data, using the chart and formulas shown in figure 8, the permitted number of daily exposures and the type of hearing protection required is determined. The range of application for each of the four exposure limits criteria W, X, Y, and Z established by the standard is explained in the table located in the upper right corner of figure 8. As per OSHA requirements, any peak sound pressure level in excess of 140 dBP (Criterion "W") requires hearing protection. Double hearing protection is required when the number of exposures per day exceed defined maxima for single hearing protection.

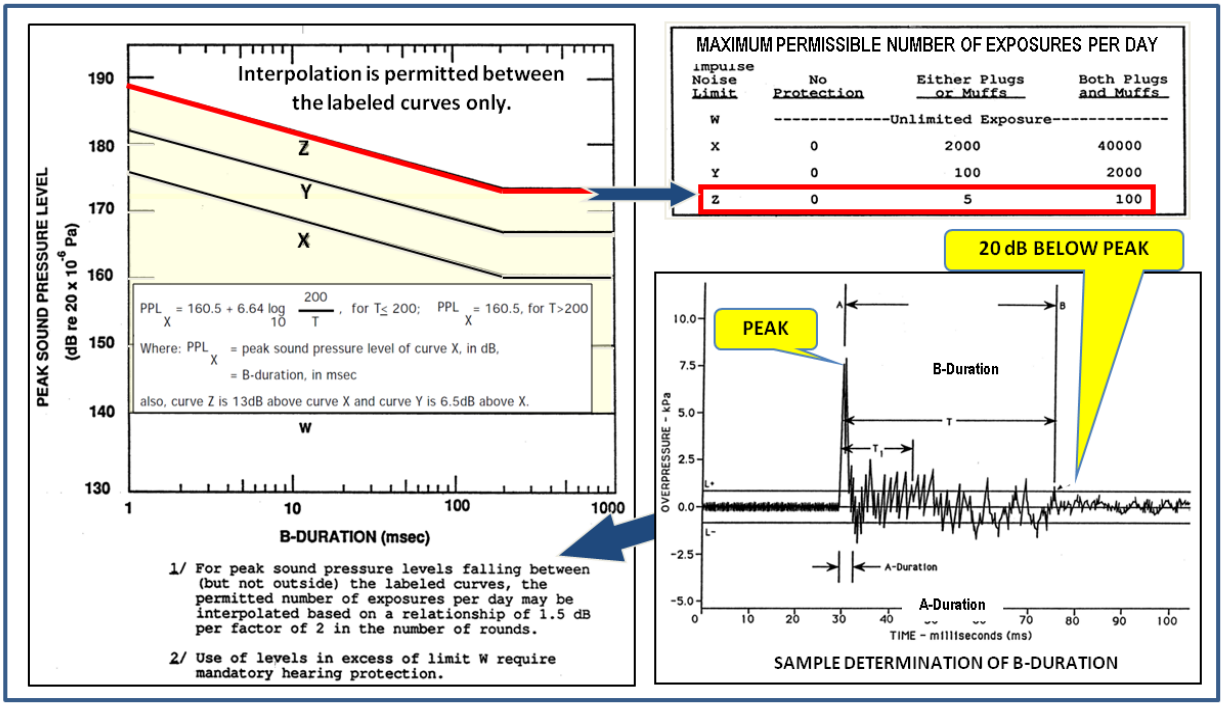

Figure 8. Requirement 4 of MIL-STD-1474D—peak sound pressure levels, B-duration limits, and daily exposure limits for impulse noise.

The effect of hearing protection on the level of impulse noise under the protector has caused considerable debate in the literature. However, this debate can be summarized by stating that peak sound pressure level attenuation, NRR data, nor L_{eq} data provide a good estimate of protector effectiveness in attenuating impulse noise. All three criteria underestimate the actual protection since the impulses under the protector have both longer rise time and decay time in comparison to the impinging impulse (Johnson and Patterson, 1992; Pekkarinen et al., 1992). As a result, the impulse under the muff may be less damaging and the proper estimate of its damaging potential has to include its modified time history. In contrast, a very strong blast of pressure may break the seal between the protector and the skin leading to increased hearing damage. In general, there is a complex relationship between the type of impulse noise (type of weapon), the type of hearing protector, the user's motivation, and the operational conditions, and any widely acceptable DRC must capture this relationship (Johnson, 2000).

Unfortunately, despite overwhelming evidence against the viability of MIL-STD-1474D, there are some attempts by the medical community to defend MIL-STD-1474D as the effective *de facto* military DRC for impulse noise. Most recently Ahroon, et al. (2011) analyzed hearing loss data for a few U.S. Army military occupational specialties (MOS), which involve some exposure to high-level impulses from various weapons. Based on audiological data, they reported that a substantial number of Soldiers on active duty have sustained some amount of hearing loss as described by an H-2 or H-3 hearing profile. The authors concluded that "now is not the time to relax the DRC for continuous or impulsive noise exposures." However, this conclusion

regarding impulse noise exposure is not supported by any acceptable evidence. There are no data provided by the authors as to the levels of either steady-state or impulse noise to which the studied Soldiers were exposed. For example, the reported hearing loss could be incurred by exposure to excessive steady-state noises alone. No information is provided regarding the length and history of the military service of the individuals included in the database. Likewise, there are no data or evidence suggesting hearing protection was consistently and correctly worn. The only conclusion that can reasonably be reached on the basis of the analyzed data is that the U.S. Army hearing conservation program is ineffective. In addition, by its lack of specificity, the paper provides indirect support to the notion that the current MIL-STD-1474D is too limited to be a useful tool in trauma and impulse-noise-induced hearing loss protection.

4.4 New Criteria for Quantifying Impulse Noise Exposure

One of the important, though controversial, parameters of the impulse hazard criteria is the effective duration of the impulse. Effective impulse duration has been extensively studied in regard to muzzle blast. Since the days of the CHABA (1968) report on impulse noise exposure, researchers attempting to quantify hazard on the basis of impulse time history have developed several measures of the effective duration of the muzzle blast. The four most common measures of impulse waveform duration used in noise hazard calculations, durations A, B, C, and D, have been described in section 2.2.2.

4.4.1 Pfander and Smoorenburg Criteria

The use of A- and B-duration in calculating noise hazard by CHABA (1968) and MIL-STD-1474D has been described previously. C- and D-duration were introduced, respectively, by Pfander et al. (1975) and Smoorenburg (1982) as alternatives to CHABA and MIL-STD-1474D criteria. The Pfander criterion, primarily used by the German armed forces, uses the C-duration to determine the duration of the event. It does not differentiate between reverberant or free field exposures. Both criteria use peak pressure and a measure of duration. The Smoorenburg criterion (developed in the Netherlands) uses the "D" duration for the determination of the exposure duration and, like the Pfander criterion, it does not differentiate between free field and reverberant conditions. However, these two criteria, CHABA, and MIL-STD-1474D do not take into consideration the waveform's behavior within the predetermined duration limits.

It should be noted that after subtracting an assumed attenuation value of the hearing protector, all these criteria may apply to the unprotected ear (e.g., Strasser, 2005, figure 19) and can be used as such in agreement with formal legislation as long as the impulse noise level at the ear is <140 dBP. However, there is some agreement in the literature that the 140 dBP could be reasonably exceeded for very short impulses without high probability of the resulting PTS.

The relation between the CHABA (1968), Pfander et al. (1980), and Smoorenburg (1982) criteria for the unprotected ear is shown in figure 9. A "Z" curve of MIL-STD-1474D is also shown for comparison. The MIL-STD-1474D curve for the protected ear is ~20 dB higher than the other

classical DRCs, which are shown for the unprotected ear. In comparing these curves one should keep in mind that double hearing protection and even single hearing protection typically provides much greater attenuation of impulse noise than 20 dB (MIL-STD-1474D, 1997; p. 99).

As can be seen in figure 9, the classical DRCs (CHABA, MIL-STD-1474D, Pfander, and Smoorenburg) all use the peak pressure, the duration(s) and the number of impulses measured in the free field close to the subject's ear and all result in very similar impulse noise limits. However, none of these metrics is successful in predicting noise hazard across various types of weapons. All the above criteria have been developed and verified by using small arms and they tend to overrate the danger of large-caliber weapons (Smoorenburg, 2003).

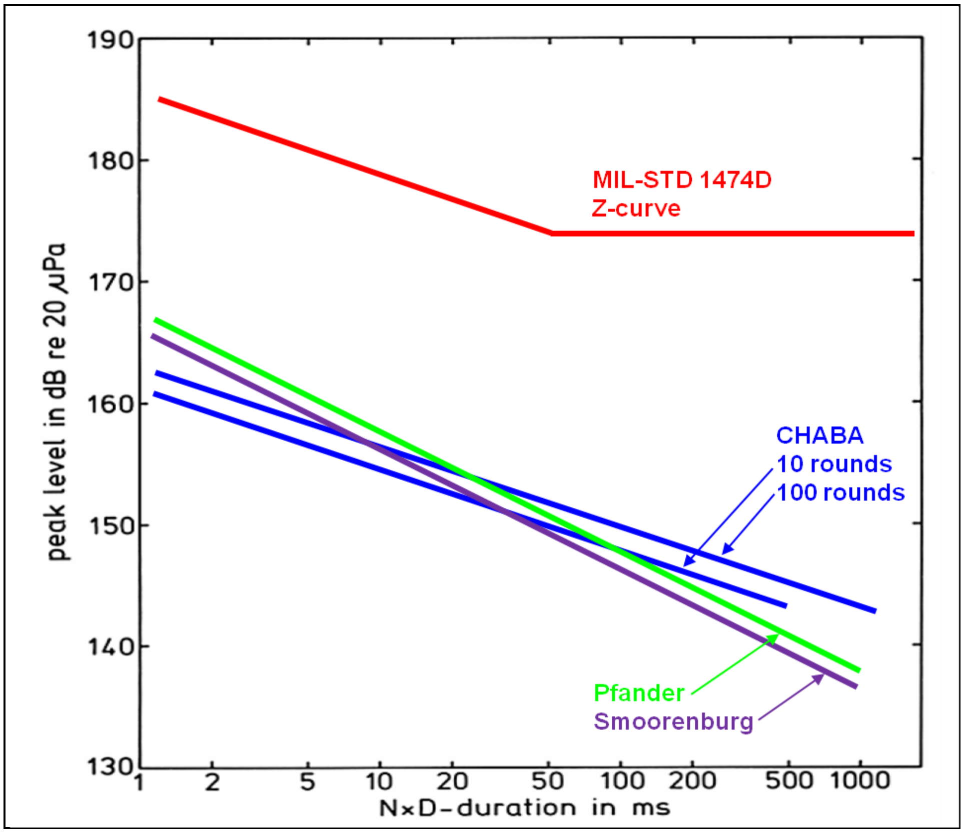

Figure 9. Comparison of classical DRC adapted from the (NATO 2003).

4.4.2 The A-weighted Energy Model

The existing characterization methods developed for assessing impulse hazard can be divided into average energy and peak pressure level methods. The most popular of the proposed energy method of hearing hazard assessment is based on the A-weighted acoustic energy (LA_{eq8}) and equal-energy hypothesis. The LA_{eq8} metrics can be applied to impulses in free sound fields or

reverberant conditions (either for small- or for large-caliber weapons), and can combine impulse and continuous noise exposures (Dancer, 2008).

The LA_{eq8} metric is normally used for predicting noise hazard caused by continuous noises and estimates the risk of developing material hearing loss after prolonged exposures to occupational noise over the course of 10 to 40 years—a worker's lifetime exposure. The attractiveness of the A-weighted acoustic energy approach is its simplicity and ability to integrate both continuous and impulsive noise. The LA_{eq8} method allows the assessment of the hazard for all classes of noises, independent of the waveform shape, independent of the peak pressure, independent of duration, and independent of zero crossings, etc.

Unfortunately, there have not been sufficient well-controlled studies to conclusively support the validity of the A-weighted acoustic energy hypothesis when humans are exposed to impulse noises (Price, 2007a). In addition, there are several reports warning that weapon noise may be more damaging than could be indicated by equal energy considerations alone (e.g., Cluff, 1980; Brüel, 1976). Most importantly, a single military impulsive event can impart more acoustic energy to a Soldier than a typical worker is exposed to over a working lifetime, and the duration and shape of this impulse are critical to the amount of resulting hearing damage. Last but not least, simultaneous use of the A-weighted energy model and the 140 dBP peak value limit for unprotected ear impulse noise exposure may put them on a collision course when the 140 dBP level is exceeded but the A-weighted energy model limit is not exceeded.

4.4.3 Ear-Model-Based Noise Hazard Criteria

4.4.3.1 The Auditory Hazard Assessment Algorithm for Humans (AHAAH)

The most advanced of the noise hazard metrics is the theoretically based Auditory Hazard Assessment Algorithm for Humans (AHAAH) (Price, 2008). AHAAH uses physical laws and a mathematical model of the ear to obtain a set of proven algorithms, which are used to determine the percentage of the population that would sustain a permanent threshold shift based on impulsive sound measurement under a variety of exposure conditions. This method accounts for impulse noise measurements in the free sound field, at the ear canal entrance, and at the tympanic membrane. Figure 10 shows the electro-acoustic analog of the human ear as used in AHAAH.

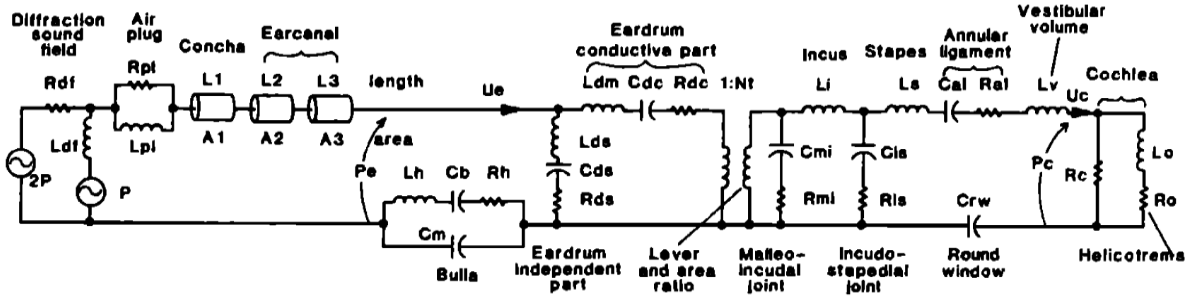

Figure 10. Circuit diagram of the electro-acoustic analog of the human ear (Price and Kalb, 1991).

AHAAH also accounts for noise attenuation introduced by a variety of HPDs and its predictions of hearing loss are in agreement with the results of all available sets of experimental data (e.g., small arms weapons, Albuquerque Studies, and automotive airbags) (Marshall et al., 1974). In addition, the physical bases of the AHAAH model make it possible to add the presence of HPDs directly into noise hazard calculations, a feature unavailable in any other criteria of noise hazard proposed to date. Due to being built as an ear-structure-based model, the AHAAH model allows the user to compare the sound waveforms measured in the free field, at the ear canal entrance, or at the eardrum position and calculate appropriate transfer functions. Measurement at the eardrum position requires the use of an acoustic manikin. Although the acoustic manikin technique is still being improved, it provides a waveform for analysis without exposing a human to danger. Alternatively, it is possible to calculate the effect of an HPD on the input waveform (Kalb, 2010, 2011). There are, in fact, many sources of variance associated with HPD use, poor fit being a prime example. Whatever choice is made with respect to how HPDs should be included, AHAAH is capable of incorporating a wide range of approaches (Price, 2011).

Another important capability of AHAAH model is that it operates in two exposure modes—warned and unwarned mode. The terms warned and unwarned refer to the state of middle ear muscles, which act primarily by stiffening the middle ear in response to a high level of noise. For a single short sound impulse arriving unexpectedly (an unwarned response), such as that from small arms, the middle ear muscle response is too slow (some tens of milliseconds to a full response) so that it essentially provides no protection from damage. Conversely, there is evidence the human middle ear muscles are conditionable, which means that they may contract when there is some signal that a sound impulse is about to arrive, i.e., a "fire" command is given or the person may be firing his own weapon and can anticipate the arrival of the impulse. AHAAH accommodates such events by including pre-contraction of the muscles before the impulse arrives (a "warned" response) (Price, 2007a).

4.4.3.2 A Hearing Protector Model for Predicting Impulsive Noise Hazard

A Hearing Protector Model for Predicting Impulsive Noise Hazard (HPMfPINH) is an add-on module to the AHAAH model. The model is based on the same modeling concept as the AHAAH model and the effect of a specific hearing protector is calculated using an electro-acoustic lumped-parameter circuit-model of HPD insertion-loss using real ear attenuation at threshold (REAT) as the input data. The basic structure of the HPMfPINH is shown in figure 11.

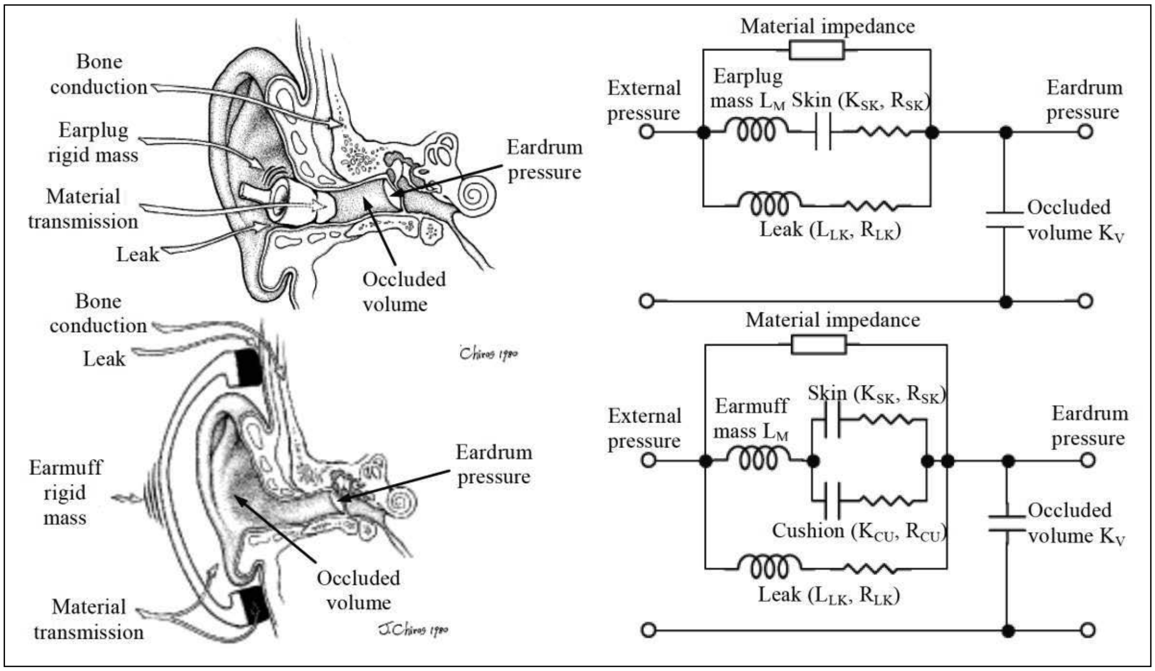

Figure 11. Acoustical and electrical diagrams of earplug and earmuff models (Kalb, 2011).

In the model shown, the energy flow through the HPD propagates along three parallel paths, each assumed behaving like a piston: (1) the rigid protector mass moving against the skin, (2) leakage volume at the contact area with the skin, and (3) transmission loss through the protector material (a second piston within the rigid piston). Paths 1, 2, and 3 are dominant contributors to inserted loss caused by the HPD at low, middle, and high frequencies, respectively. Individual elements of the electro-acoustic circuit are adjusted so overall transmission loss introduced by the HPD matches REAT data. In the development process of the HPD module, the electro-acoustic analog circuits have been established for 384 REAT datasets (shown in figure 12) collected using the ANSI S12.6 (ANSI, 2008) method B (naive users), which constituted the basis for determining statistical frequency distributions of occluded volume and leakage elements (Royster et al., 1996).

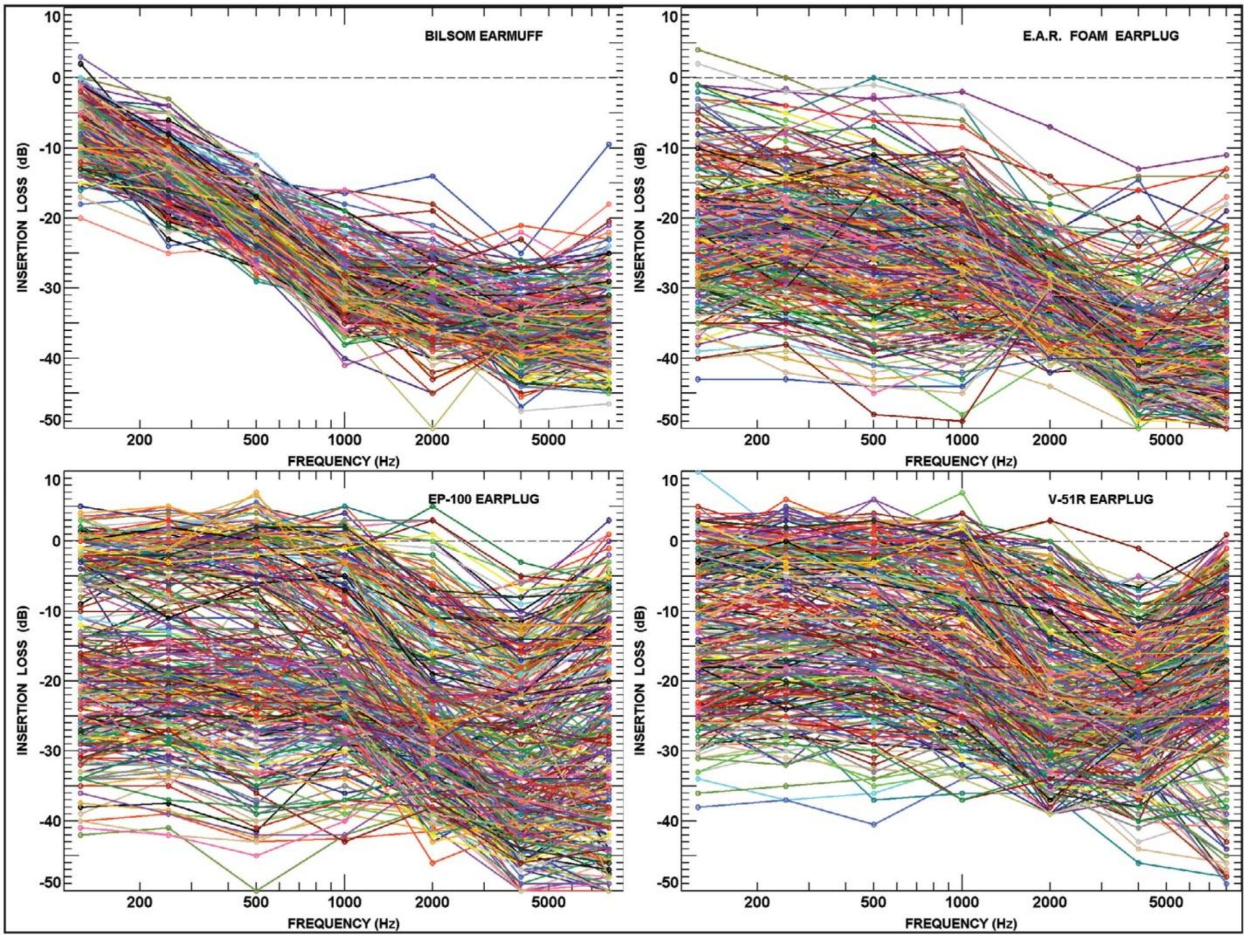

Figure 12. Insertion loss REAT data of four hearing protectors (each with 384 subjects) measured in the Interlab Study (Royster et al., 1996).

For a given free-field impulsive noise, the model pressure predictions under the protector are compared to measurements of acoustical manikin ears to check the validity of assumptions. The hearing hazards of the measured waveforms and the predicted waveforms are calculated using the basic AHAAH model. The result is a cumulative frequency distribution of hazard based on the user fit data, which is useful in finding the best protector for a given impulsive noise.

This technique of applying the hearing protector model to multiple insertion loss cases gives the distributions of electro-acoustic values, which describe the variability of fit. Applying these multiple fits to a given free-field waveform gives cumulative distributions of hearing hazard, which describe the percentage of the population that are protected. As a result, this predictive modeling technique, when combined with AHAAH, permits quantification of hearing loss while wearing HPDs.

Any DRC attempting to characterize hearing damage risk while using HPDs must accurately reflect the large variance that actually occurs when people use HPDs. The magnitude of this variance is indicated in figure 12. AHAAH, with the HPMfPINH, represents the only existing

accurate method of evaluating the actual variance in HPD performance, and thus, is the only approach which can provide the essential variance element needed in an accurate DRC for persons using HPDs.

5. Operational Impact of Damage Risk Criteria

Operationally, the selection of the proper DRC can mean the difference between mission success and failure or life and death. For example, U.S. Army tactics permits use of shoulder-fired anti-tank weapons from within enclosures. Depending upon which of the proposed DRC are used, Soldiers may be permitted to fire from within enclosures or firing from the enclosure may be prohibited or severely limited. Figure 13 summarizes the impact of various DRCs on the number of anti-tank rocket rounds permitted to be fired daily under the above conditions while Soldiers wear single hearing protection devices. As it can be seen, an AHAAH-based DRC permits the safe firing of a few rounds from the standing or kneeling positions, a procedure which is consistent with current military experience. In contrast, the other standards, with one exception, prohibit firing. The over-conservative nature of assessments for this impulse with various DRC is consistent with the research that has shown the other methods tend to over-predict hazard (Price, 2007b). The traditional methods thus prohibit the use of an effective weapon system that has been demonstrated to be safe.

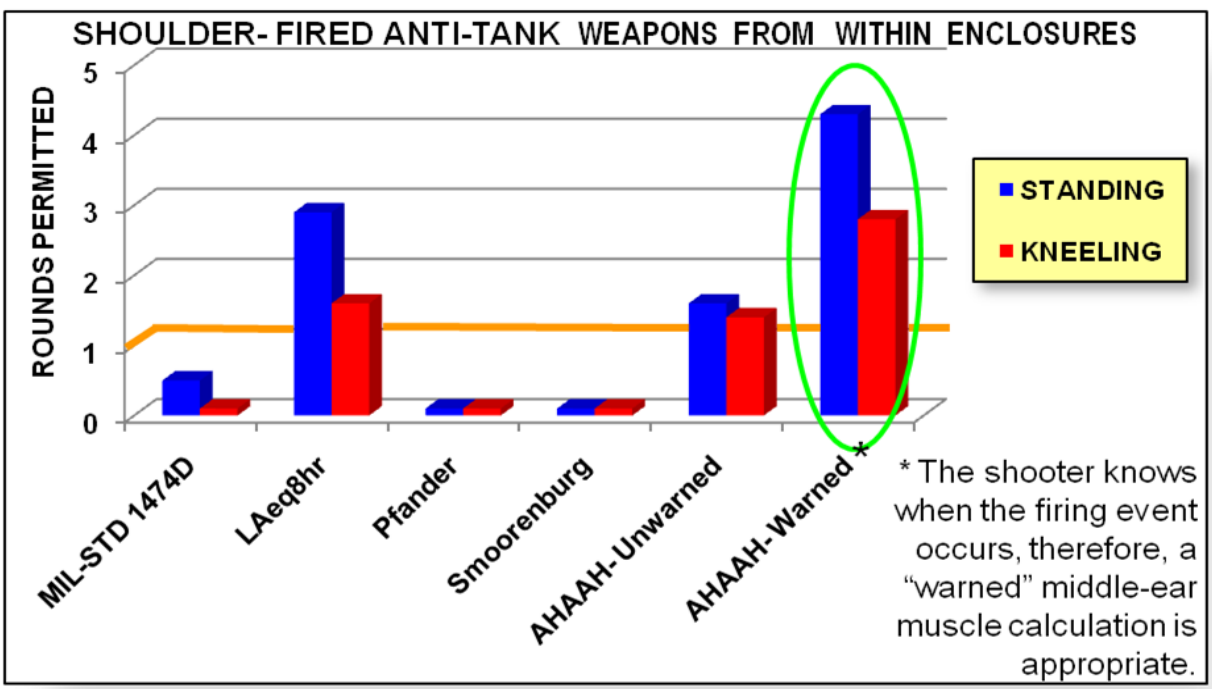

Figure 13. Firing from enclosures: comparison of operational impacts of various DRCs while wearing single hearing protection devices.

Notes: FF= free-field, NA = manikin measurement not permitted.

The duration-based or A-weighted energy DRC approaches fail to account for the actual intricate physiological and physics-based performance of the ear, which is essential to accurately address the true complexity of the ear's response to intense sounds at the level of weapons fire (155 to 185 dBP). These methods assume "standard" Friedlander waveforms, which permit simple peak, duration, and integrated energy measurements. They ignore, however, such important properties as the frequency content or number of "zero crossings" of the waveform. They were also developed to account for noise hazard produced by a very limited range of weapons. In comparison, AHAAH's theoretical approach assures generalizability across all types of weapons and to new impulses that may vary from those upon which it was initially tested. In addition, AHAAH includes such important properties of the human ear as the nonlinearity of the stapes' action at high intensities that peak-clips the energy arriving at the cochlea. Most importantly, AHAAH has features providing engineering insight into the loss process, which, in turn, will result in safer, more effective designs of hearing protection devices and use strategies.

As a primary user of the hearing hazard DRC, the U.S. Army must assure the adopted DRC meets all requirements to protect 95% of the exposed population from permanent auditory damage while permitting fielding of lethal weapons systems so critical to national defense.

6. Summary and Conclusions

For over four decades, scientists, preventative medicine officers, health hazard assessors, weapons developers, and warfighters have sought a scientifically based damage risk criteria specifically created to meet the unique needs of the military weapons and medical communities. These communities have been diametrically opposed to each other, with weapons designers and warfighters seeking the ultimate offensive weapon regardless of noise and the medical community seeking to limit weapons designers to systems, which, when used as intended, cause no hearing loss to the weapons systems operators.

For the U.S. military, the MIL-STD-1474D serves as a *de facto* 95% DRC in the absence of a formally approved criteria issued by the military medical community. While the MIL-STD-1474D standard is acknowledged as overly protective and is based on questionable science, it has served for decades—primarily due to lack of agreement on a replacement. Regardless of the DRC selected, it is senseless to develop a DRC without agreement between the materiel developers and the medical community. Any DRC must permit maximizing Solder lethality while minimizing hearing loss.

The main drawback of all DRCs proposed to date (CHABA, Pfander, Smoorenburg, TWA, etc.) is the fact that they are based on physical measurements of the waveform produced by the weapons system under specific conditions. All of these criteria ignore the intricacies of the

waveform produced by the weapon's blast. Further, these criteria disregard the complex physiology of the human ear.

The sole exception is the AHAAH. The AHAAH concept acknowledges the distinctive properties of the human ear, which limit damage when operating at the extremely high levels of impulse sounds typical of military weapons systems. The AHAAH model was developed as a first-principle, electro-acoustic analog of the ear that includes the basic research insights into the ear's function at high pressure levels. The AHAAH concept takes into consideration intracochlear loss mechanisms and mechanical stress within the organ of Corti. At the stimulus levels typically produced by military weapons, the conductive path exhibits spectral tuning, middle ear muscle attenuation of transmission, and peak-limited displacements of stapes. The value of AHAAH approach was summarized by Johnson (2000, p. 2-2) stating that "for exposures, in which the peak level is above 140 dBP, the auditory modeling method must be used."

The AHAAH has been used internationally for over 10 years within the armaments community, has been incorporated by the Society of Automotive Engineers (SAE, 2003) in their recommended procedures for airbag design, and is being proposed as an ANSI standard for intense noise exposure. According to Smoorenburg (2003), the AHAAH value lies in that "it accounts for a decrease in risk of hearing damage with increasing low-frequency energy in the impulse sounds."

In our opinion, the broad and weapon-independent DRC requirements of the U.S. Army are best met by modeling of the ear response to the arriving acoustic blast waves. An extensive analysis of all available impulse-noise-related human hearing loss data demonstrated that AHAAH correctly predicted hearing loss in all except for three individual cases (out of 1000 cases compared) (Price, 2007b). Further, in all three cases, the AHAAH over-predicted actual hazard. In analyzing the dataset collected during the landmark Albuquerque Study (Patterson et al., 1994), the AHAAH achieved prediction accuracy of 94% while the accuracy of other existing and proposed methods varied from 25% to 42% (Price, 2011). Most importantly, the AHAAH has never underestimated the hazard from high level impulse noise. In summary, the current version of the AHAAH is a much better solution than anything else that has been proposed and it is highly probably that the final solution will be based on the AHAAH model. As such, the current version of the AHAAH should be accepted as the U.S. Army interim impulse noise DRC. Failure to do so indicates a lack of leadership in the scientific and medical communities of the U.S. Army, both of whom are responsible for the survivability and lethality of its Soldiers.

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Lists of Symbols, Abbreviations, and Acronyms

AHAAH	Auditory Hazard Assessment Algorithm for Humans
ANR	Active Noise Reduction
ANSI	American National Standards Institute
AR	acoustic reflex
ASA	American Standards Association
CAE	Combat Arms Earplug
CHABA	Committee on Hearing and Bio-acoustics
DRC	Damage Risk Criteria
EPA	Environmental Protection Agency
Hb	hemoglobin
HCC	Hearing Conservation Criteria
HEL	Human Engineering Laboratory
HHA	Health Hazard Assessment
HL	hearing levels
HNL	Hazardous Noise Limits
HPDs	hearing protection devices
HPMfPINH	Hearing Protector Model for Predicting Impulsive Noise Hazard
MAAWS	Multi-role Anti-armor Antipersonnel Weapon System
MOS	military occupational specialties
MSHA	Mine Safety and Health Administration
NATO	North Atlantic Treaty Organization
NEL	Noise Exposure Limits
NIOSH	U.S. National Institute for Occupational Safety and Health
NRR	noise reduction ratio

OSHA	U.S. Occupational Safety and Health Administration
PEL	permissible exposure level
PTS	Permanent Threshold Shift
REAT	real ear attenuation at threshold
RMS	root-mean-squared
SPL	sound pressure level
TTS	Temporary Threshold Shift
TWA	time-weighted average

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